Journal of the Royal Society of Western Australia, 76 : 71-76; 1993

Salinity trend of the Williams River, Western Australia

B Yu[1] & D T Neil[2]

[1]Faculty of Environmental Sciences, Griffith University, Nathan, QLD 4111
[2]Department of Geographical Sciences and Planning, The University of Queensland, St Lucia, QLD 4072

Manuscript received January 1993; accepted July 1993

Abstract

The Williams River has one of the highest stream salinity levels and one of the highest rates of salinity increase in southwest Western Australia. Temporal variation of stream salinity of the Williams River at Saddleback Road Bridge was examined by: 1) contrasting two periods with similar average flows; and 2) comparing trends in both salinity and stream flow for various periods. The contrast between flow-weighted average salinity for 1969-73 and for 1984-88 shows an increase of 51 ± 0.7 mg L^{-1} yr^{-1}, which is only 54 % of the previously published figure. The high rate of salinity increase previously documented is, to a large extent, a result of persistent low flows in the late 1970s. The 1980s have been a period of decreasing stream salinity as a consequence of increased flow. Variations in salinity are closely related to stream flow conditions. For the period of record (1967-90) the trend over time explains only 5.5 % of the variation in annual average salinity, whereas stream flow variation accounts for 74 % of the variation in salinity. The salinity trend is inversely related to that in stream flow. The effect of stream flow on salinity highlights the importance of long-term water quality monitoring.

Introduction

The Williams River catchment has an area of approximately 1,500 km^2, and lies 150 km south-east of Perth (Fig 1). The river flows westward, mostly through agricultural land. Roughly 90 % of the catchment has been cleared for grazing and cereal production (Public Works Dept. WA 1984). Mean annual rainfall is about 500 mm in the headwaters area and increases to about 800 mm near the Murray River confluence (Collins 1974). At Williams, which is located near the centre of the catchment, winter rainfall (June to August) constitutes more than half of the annual total and summer rainfall (December to February) constitutes no more than 10 % of the annual total.

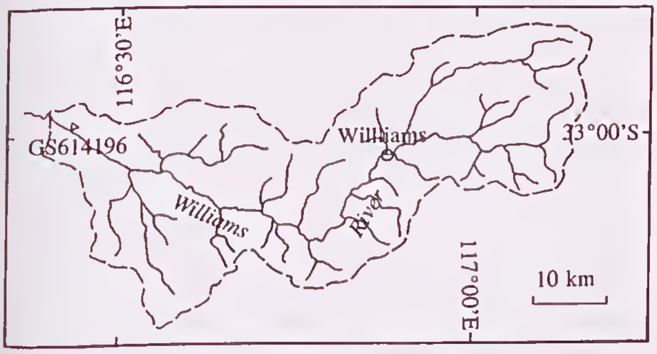

Figure 1. Location map of the Williams River, Western Australia.

The Williams River has one of the highest rates of increase in stream salinity (95 mg L^{-1} yr^{-1} for the period 1966-86) in southwest Western Australia (Schofield *et al.* 1988, Schofield & Ruprecht 1989). With an average salinity of about 3,000 mg L^{-1}, the Williams River has been classified as brackish with little potential for future development as a source of domestic water supply (Schofield *et al.* 1988).

It is well known that an inverse relationship exists between the concentration of many stream solutes and stream flow because of the dilution effects of stream flow. For example, time series analysis of the salinity trend of the River Murray at Morgan (South Australia) showed a strong, inverse relationship between salinity and stream flow on a monthly basis (Cunningham & Morton 1983). In southwest Western Australia, a close relationship between stream flow and chloride load was reported for both cleared and uncleared catchments (McPherson & Peck 1987). Therefore, the effect of stream flow must be evaluated before trends in solute concentrations can be assessed. In this paper, two approaches were used to evaluate stream salinity trends in the Williams River. First, we examined the salinity-stream flow relationship for two periods with similar stream flow conditions and the salinity increase for a given stream flow was determined. Secondly, trends in both salinity and stream flow were compared for different periods to identify the effect of stream flow on stream salinity.

Salinity data provided by the Water Authority of Western Australia were measurements of total soluble salts (TSS), in units of milligrams per litre (mg L^{-1}). Salinity was determined through ion analysis for 3.3% of the samples, the rest derived from electrical conductivity measurements (R Dowd of WAWA, pers. comm.). In this paper, we use the terms salinity and TSS interchangeably.

©Royal Society of Western Australia 1993

Contrasting Period Approach

To overcome fluctuations on small time scales, data for a certain period are sometimes aggregated to facilitate comparison with those in another period. For example, Pittock (1983) compared monthly rainfall for two contrasting periods (1913-45 versus 1946-78) to evaluate the likely change in rainfall due to the enhanced greenhouse effect. Likewise, Yu and Neil (1993a) contrasted rainfall total and high intensity rainfall for the periods 1911-50 and 1951-90 to establish the trends in southwest Western Australian rainfall.

A plot of the number of salinity samples per annum and annual stream flow of the Williams River at Saddleback Road Bridge (GS614196, catchment area = 1,437 km^2) shows that 1975-80 is a period of intense salinity measurement and is also the period of lowest flow on record (Fig 2). Between July 1975 and November 1980, an average of 25 samples were taken per month in contrast to 1.6 and 1.8 samples per month for the periods May 1966 - June 1975 and December 1980 - September 1990, respectively. Average annual stream flow for the period 1976-80 was 20 mm, the lowest for any 5-year period in the 24 years of record (1967-90). The period 1975-80 likewise had the lowest stream flow for any 6-year period on record (23 mm). When choosing contrasting periods for the analysis of the Williams River salinity trend, we considered whether the two periods were well separated in time and whether the average stream flow and number of samples for the two periods contrasted were comparable.

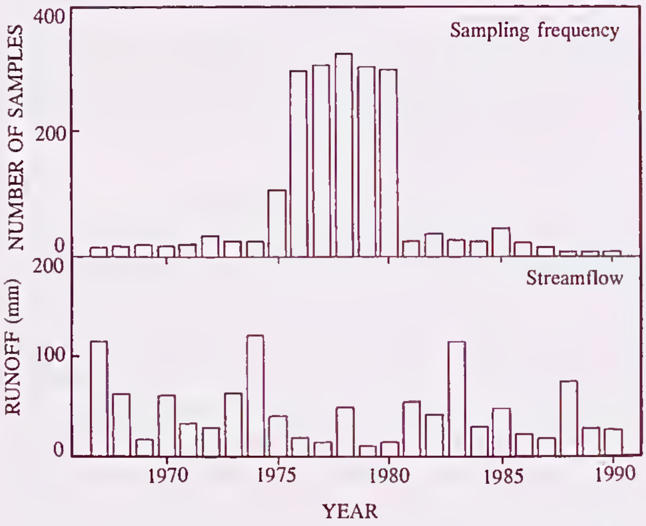

Figure 2. Salinity sampling frequency and annual stream flow at Saddleback Road Bridge (GS614196).

The periods 1969-73 and 1984-88 with a separation of 15 years (between mid-points) were chosen. Average annual stream flow for these two 5-year periods was 41 mm and 37 mm, respectively, in comparison with the long-term (24 years) average of 46 mm yr^{-1}. Furthermore, if more than one sample was taken on any given day, only the first sample was retained in the data set to ensure that samples were taken independently. As a result, a total of 28 measurements were discarded, and the number of samples for each of the two periods was 95 and 97, respectively. Three methods were used to assess the salinity changes. 1) Rating curves for the two periods were compared. 2) Flow-weighted average concentrations for the two periods were compared. 3) The median test was used to estimate changes in median salinity values for the contrasted periods and for different flow conditions.

Salinity-stream flow relationship

As noted elsewhere (Yu & Neil 1993b) a simple log-linear model is inadequate to describe the relationship between salinity and stream flow in the Williams River. A second order term was introduced to fit the data, resulting in the following regression equations:

Period I (1969-73):

$$\log C = 3.6 - 0.22 \log Q - 0.084 (\log Q)^2, r^2 = 0.61; \quad (1)$$

Period II(1984-88):

$$\log C = 3.7 - 0.21 \log Q - 0.093 (\log Q)^2, r^2 = 0.73, \quad (2)$$

where C is TSS in mg L^{-1} and Q is instantaneous stream flow in m^3 s^{-1}. Standard errors of the estimate for the two regression equations are 0.016 and 0.07, respectively.

It can be seen from the scatter plot and fitted quadratic equations that maximum salinity occurs during intermediate flows for both periods analysed (Fig 3). To use these regression equations to estimate salinity for a given stream flow requires a bias correction factor due to the log-transformation (Ferguson 1986; Koch & Smillie 1986). Correction factors using the nonparametric method (Koch & Smillie 1986) for the two periods are 1.04 and 1.02, respectively. The rate of increase in salinity between the two periods varies in relation to stream flow (Fig 4). The rate of increase was standardised using its standard error (Fig 4) so that its value greater than 1.96 indicates a significant increase at 0.05 level. The maximum salinity increase of 69±18 mg L^{-1} yr^{-1} occurs for stream flow between 0.25 and 0.5 m^3 s^{-1}. For stream flow of 0.01 m^3 s^{-1} the increase in salinity is 21±27 mg L^{-1} yr^{-1} and for stream flow of 10 m^3 s^{-1} the increase is 35±11 mg L^{-1} yr^{-1}. For the average flow (1.8 m^3 s^{-1}) the change in salinity is 57±1 mg L^{-1} yr^{-1}.

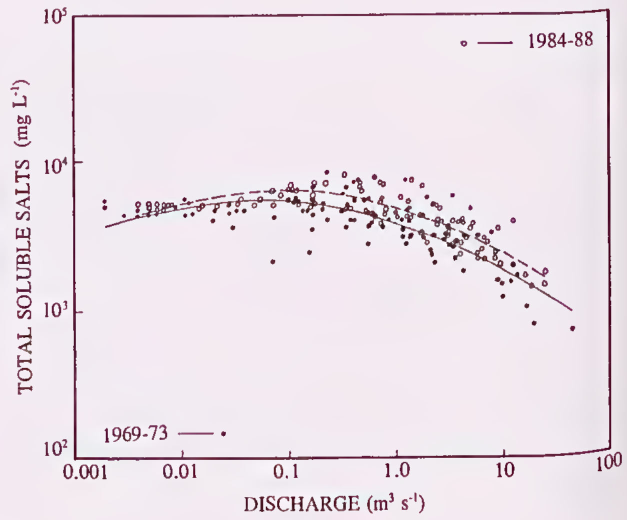

Figure 3. Comparison of salinity rating curves for the periods 1969-73 and 1984-88.

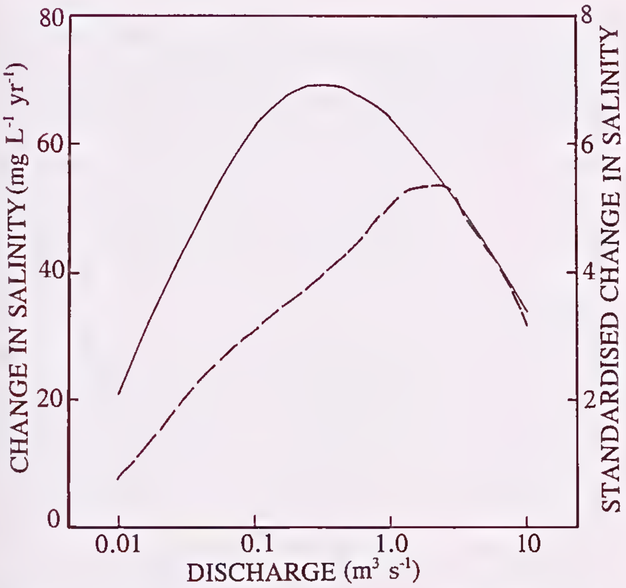

Figure 4. The rate of salinity increase (solid line) and the standardised rate of salinity increase (dashed line) between 1969-73 and 1984-88 in relation to stream flow.

Flow-weighted average salinity

Equations 1 and 2 were used as rating curves to calculate the total load for each of the two periods, respectively. Empirical rating curves, usually simple power functions, are commonly used to define the variation of concentration with stream flow in each transport mode (Richards 1982) and these rating curves have been widely used to calculate sediment loads of rivers (*e.g.* Walling 1977, Linsley *et al.* 1988). No systematic errors in salinity estimates were introduced by using average daily flows. Average salinity was estimated by dividing the total load for the two 5-year periods by the corresponding total stream flow volume. Assuming that daily salt loads are mutually independent, the variance of flow-weighted average salinity, C_{av}, is given by:

$$\mathrm{Var}(C_{av}) = \frac{\Sigma\, Q_i^2\, \mathrm{Var}(C_i)}{(\Sigma\, Q_i)^2}$$

where Q_i represents daily flow, and C_i estimated daily TSS. Thus the standard error of the 5-year average salinity can be estimated using this relationship. The flow-weighted average salinity was 2,287±8 mg L^{-1} for the first period and 3,055±6 mg L^{-1} for the second period, which yields a significant average increase of 51±0.7 mg L^{-1} yr^{-1}, or 34%, over the 15-year period.

Median test

Since water samples were effectively taken randomly, the median test (*e.g.* Gibbons 1971) may be used to determine whether the median TSS for the second period is significantly higher than that for the first period and to calculate the confidence interval for the difference in the median TSS. The test was performed on a common flow range (*i.e.* 0.0035 - 25 m^3 s^{-1}) for both periods. Sample size within this range for the two periods is reduced to 91 and 97, respectively. Median salinity increased from 4,010 mg L^{-1} for the first period to 4,710 mg L^{-1} for the second period. Thus, the median test showed an increase of 47 mg L^{-1} yr^{-1} with a confidence interval of -1.6 to 54 mg L^{-1} yr^{-1} (confidence level = 0.856) and such an increase was not significant at 0.1 level (p-value = 0.121).

Based on daily and instantaneous stream flow and salinity measurements for the two contrasting periods, we have shown that the salinity increase is likely to be in the range 47-57 mg L^{-1} yr^{-1}. The lower and upper bounds of this range are based on the median test and on the rate of increase at average flow, respectively. 51±0.7 mg L^{-1} yr^{-1}, based on the flow-weighted average, is the most reliable because the standard error of this estimate is lowest.

Varying Period Approach

To eliminate seasonal and other small-scale variations in stream salinity, annual flow-weighted salinity was estimated using the rating curve method. As noted in comparisons using the contrasting period approach, bias in the data set, due to an order of magnitude greater sampling frequency in the period 1975-80, should be removed before analysis. For this analysis, a bias-free sub-sample of the data set was obtained by extracting one observation per month from samples collected closest to the 1st of each month. This operation was repeated for the 15th and 30th of each month. Three separate rating curves (n = 36 for each) were then calculated for each of three year periods using each of these sub-samples. Flow-weighted salinity for each year of record was calculated from each of the three rating curves for each three year period. The annual flow-weighted salinity (Fig 5) used for ensuing analysis is an arithmetic mean of these three estimates. The average difference between annual salinity estimates, calculated from three sub-samples of the data set, is about 10 %.

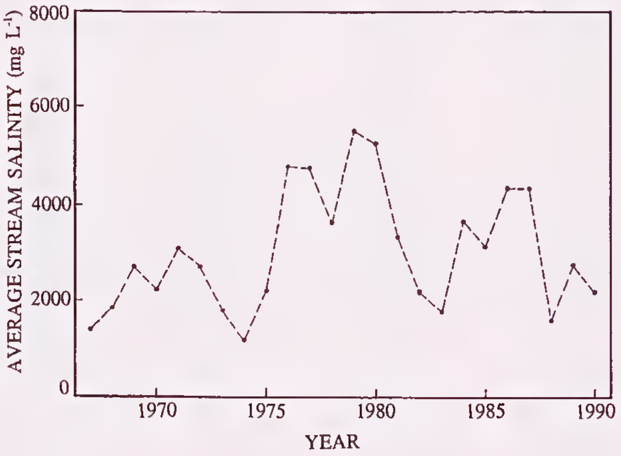

Figure 5. Time series of annual flow-weighted average salinity of the Williams River.

The long-term (1967-90) flow-weighted average salinity for the Williams River is 2,330 mg L^{-1}, varying from a minimum of 1,177 mg L^{-1} in 1974 to a maximum of 5,493 mg L^{-1} in 1979.

Standard statistical tests were applied to annual flow-weighted average salinity and stream flow to identify and quantify stream salinity trends for varying periods of record. We used linear regression between concentration and time to determine the rate of change of salinity over time and Spearman's rank correlation coefficient to test for the occurrence of a trend in stream salinity (Table 1). The first part of Table 1 represents the conclusion regarding the trend in salinity which would have been reached at various times in the past, given commencement of salinity monitoring in 1967. The second part of the table represents the conclusion regarding salinity trend which would have been appropriate in 1990 if the monitoring program had begun at various times after 1967. Annual flow-weighted stream salinity has not changed significantly over the period 1967-90. Salinity trend varies considerably for different periods. For example, between 1967 and 1978-82, stream salinity increased significantly (at 0.05 level) and the maximum rate of increase was as high as 268 mg L^{-1} yr^{-1} (1967-80). In contrast, stream salinity has significantly decreased over time (again at 0.05 level) between 1976-77 and 1990 with a maximum rate of decrease of 165 mg L^{-1} yr^{-1} (1976-90). Inferences regarding trends in salinity are, therefore, strongly dependent on the sampling period in question.

Table 1

Summary of salinity trends, their significance levels and correlation between salinity and stream flow for different periods.

r_s (C vs. T): Spearman's rank correlation coefficient between flow-weighted average salinity and time.

r_s (C vs. Q): Spearman's rank correlation coefficient between flow-weighted average salinity and stream flow.

* significant at 0.05 level ** significant at 0.01 level

Period	Rate of Change (mg L^{-1} yr^{-1})	r_s (C vs. T)	r_s (C vs. Q)
1967-76	142 ± 108	0.24	-0.89 **
1967-77	212 ± 97	0.42	-0.90 **
1967-78	202 ± 81 *	0.53	-0.84 **
1967-79	251 ± 74 **	0.63*	-0.87 **
1967-80	268 ± 64 **	0.70**	-0.90 **
1967-81	224 ± 61 **	0.70**	-0.86 **
1967-82	164 ± 64 *	0.54*	-0.84 **
1967-83	112 ± 64	0.34	-0.87 **
1967-84	106 ± 57	0.40	-0.87 **
1967-85	92 ± 51	0.42	-0.83 **
1967-86	98 ± 46 *	0.45*	-0.84 **
1967-87	101 ± 42 *	0.48*	-0.86 **
1967-88	70 ± 42	0.33	-0.88 **
1967-89	57 ± 39	0.32	-0.86 **
1967-90	42 ± 37	0.24	-0.83 **
1981-90	-23 ± 116	-0.05	-0.70 **
1980-90	-122 ± 110	-0.29	-0.77 **
1979-90	-185 ± 99	-0.45	-0.83 **
1978-90	-155 ± 85	-0.43	-0.77 **
1977-90	-163 ± 73 *	-0.52	-0.82 **
1976-90	-165 ± 63 *	-0.59*	-0.84 **
1975-90	-107 ± 65	-0.43	-0.82 **
1974-90	-45 ± 68	-0.19	-0.85 **
1973-90	-11 ± 63	-0.06	-0.87 **
1972-90	-1 ± 57	-0.01	-0.84 **
1971-90	1 ± 51	0.01	-0.82 **
1970-90	13 ± 47	0.04	-0.82 **
1969-90	17 ± 43	0.08	-0.77 **
1968-90	29 ± 39	0.15	-0.80 **
1967-90	42 ± 37	0.24	-0.83 **

Only 5.5% of variation in annual flow-weighted average salinity can be explained using the linear model to relate salinity to time for the period 1967-90. This is in stark contrast to 74% of variation in annual flow-weighted average salinity that can be explained by annual stream flow using a simple log-linear model for the same period. A plot of percentage of variation of annual salinity explained by annual flows against that explained by time for various periods (Fig 6) shows that a simple log-linear model using annual flows explains between 75 and 85 % of salinity variation for most periods; while a linear trend never explains more than 60 % of salinity variation for any of the periods considered. Similarly, the rank correlation between salinity and time is less than 0.70 for all of the periods examined, whereas the correlation between salinity and stream flow is never less than 0.70 and it can be as high as 0.90 according to the time period considered. A significant correlation (at 0.05 level) exists between salinity and stream flow for all of the periods investigated (Table 1).

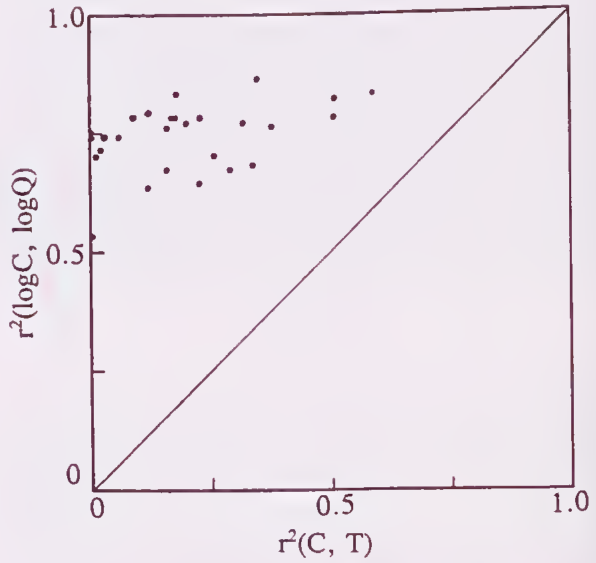

Figure 6. The relationship between percentage of salinity variation explained by a simple log-linear model based on annual flows and that explained by salinity trend.

With respect to trend in stream flow, annual stream flow significantly decreased (-4.3±2.1 mm yr^{-1}; Spearman's r_s at 0.05 level) between 1967 and 1980 and no significant change in annual stream flow was detected for any other period. Changes in salinity and flow for various periods, expressed as a percentage of their respective long-term averages, are closely related (Fig 7). There is a clear inverse relationship between change in stream flow and change in salinity when the change in salinity is significant. The inverse relationship between the trends in flow and salinity suggests that an increase in salinity is a likely result of a decrease in stream flow, *ceteris paribus*.

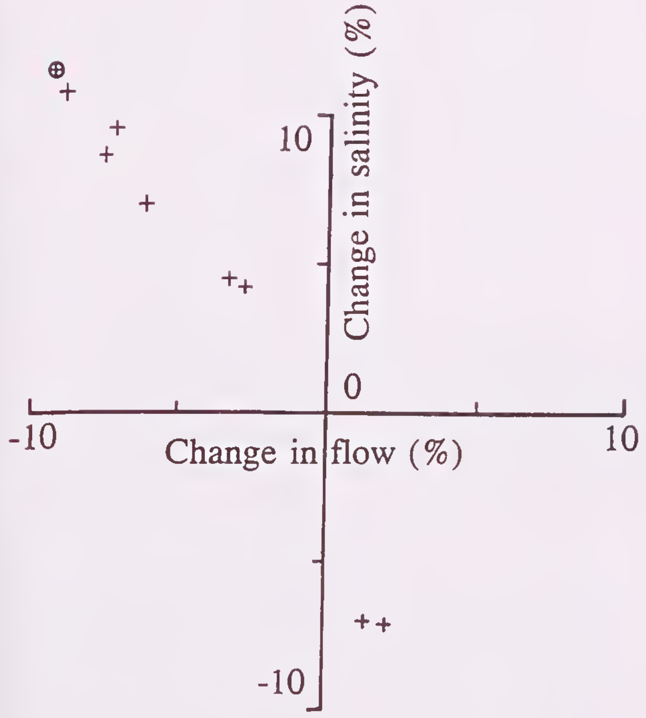

Figure 7. The relationship between trend in stream salinity and that in stream flow for various periods. Cross: only trend in salinity is statistically significant at 0.05 level; and cross and circle: trends in both salinity and flow are statistically significant at 0.05 level.

Examination of the temporal variation of salinity and stream flow for various periods thus shows that the inferred rate of change of stream salinity is highly sensitive to the period under consideration and is also strongly related to temporal variation of stream flow.

Discussion and Conclusion

Stream salinity is strongly correlated with stream flow, as demonstrated in both this and other studies. It follows that it is necessary to take account of both the variation and trend in stream flow when assessing salinity trend. In this study, several methods have been employed to estimate the change in stream salinity over the period 1967-90. The methods used, which take account of stream flow variation, yield quite consistent results, suggesting that the intrinsic change in salinity in the Williams River over the study period was an increase of about 50 mg L^{-1} yr^{-1}. Although this rate of increase is significant in terms of water quality standards, it is about half of the rate previously documented for this stream.

In the light of the strong relationship between stream flow and salinity and the consequent temporal variation in salinity, a re-examination of documented salinity trends for other rivers in the region is necessary. The regionally consistent rainfall trend (Yu & Neil 1993a) suggests that a downward revision of the salinity trend in many streams is a likely outcome. Such a reassessment should be undertaken using more rigorous statistical procedures than previously and taking account of trends in stream flow.

The variable period approach used shows that the salinity trend over time is a relatively minor component of the variation in salinity, by far the most important factor being the stream flow. However, significant salinity trends, both increasing and decreasing, have occurred during some time periods. These results reinforce the necessity of placing analysis of all water quality time series in the context of changing environmental conditions. It is also clear that refinement of our understanding of salinity in an environment of high climatic variability and uncertain climatic trends requires the maintenance of long-term data series which permit a statistically rigorous separation of the different factors contributing to stream water quality.

In conclusion, it has been shown that salinity in the Williams River has increased significantly at about 50 mg L^{-1} yr^{-1} over the period of available records. This result constitutes a downward revision by about 50% of the rate previously documented. Stream salinity is largely related to stream flow in the Williams River, with 74 % of variation in stream salinity explained by stream flow variation in contrast to only 5.5 % of stream salinity variation being explained by the salinity trend.

Acknowledgments: We are most grateful to Mr Greg May, Dr Nick Schofield and Mr Rolly Dowd of the Water Authority of WA for providing stream flow and salinity data and research reports. We also thank Dr D R Williamson of CSIRO Division of Water Resources and an anonymous reviewer for providing numerous valuable suggestions which have greatly improved the paper.

References

Collins P D K 1974 Murray River Basin Surface Water Resources Survey. Public Works Department of Western Australia.

Cunningham R B & Morton R 1983 A statistical method for the estimation of trend in salinity in the River Murray. Australian Journal of Soil Research 21: 123-32.

Ferguson R I 1986 River loads underestimated by rating curves. Water Resources Research 22: 74-76.

Gibbons J 1971 Nonparametric Statistical Inference. McGraw-Hill, New York.

Koch R W & Smillie G M 1986 Comments on "River loads underestimated by rating curves" by Ferguson R I. Water Resources Research 22: 2121-2122.

Linsley R K Jr, Kohler M A & Paulhus J L H 1988 Hydrology for Engineers. McGraw Hill, New York.

McPherson D K & Peck A J 1987 Models of the effect of clearing on salt and water export from a small catchment. Journal of Hydrology 94: 163-179.

Pittock A B 1983 Recent climatic change in Australia: Implications for a CO_2-warmed earth. Climatic Change 5:321-340.

Public Works Department of WA 1984 Streamflow Records of Western Australia to 1982 Vol 2 Basins 613-617.

Richards K 1982 Rivers: Form and Process in Alluvial Channels. Methuen, London.

Schofield N J, Ruprecht J K & Loh I C 1988 The impact of agricultural development on the salinity of surface water resources of south-west Western Australia. Water Authority of Western Australia, Report No. WS 27, 69 p.

Schofield N J & Ruprecht J K 1989 Regional analysis of stream salinisation in southwest Western Australia. Journal of Hydrology 112: 19-39.

Walling D E 1977 Assessing the accuracy of suspended sediment rating curves for a small basin. Water Resources Research 13: 531-538.

Yu B & Neil D T 1993a Long-term variations in regional rainfall in the south-west of Western Australia and the difference between average and high intensity rainfalls. International Journal of Climatology 13: 77-88.

Yu B & Neil D T 1993b Temporal and spatial variations of the total dissolved solids, Williams River, Western Australia. In: Chowdhury R N & Sivakumar M (eds.) Environmental Management, Geo-Water and Engineering Aspects. A A Balkema, Rotterdam, 245-250.